Study on the effectiveness of different control techniques for red palm weevil (*Rhynchophorous ferrugineus*)

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Date palms are critical to food systems, economics, and culture in the Arabian Peninsula, but threats such as water scarcity, soil and water salinity, low soil fertility, and pests and diseases all threaten the plant's survival and productivity – and climate change is on track to exacerbate these.

The International Center for Biosaline Agriculture (ICBA) has been carrying out research on this topic for 23 years in its UAE plantation – the longest-running large-scale experiment in the country – where it experiments with all main date palm varieties for the UAE and Saudi Arabia. Its work offers key insights into the sustainable management of date palm into the future, with a specific focus on what it will take to productively cultivate the crop using irrigation from saline water: conserving resilient genetic resources, promoting best farming practices, and enhancing fruit quality. The value of date palms as a cash crop is undeniable, but their growth is seriously threatened by the red palm weevil (RPW) Rhynchophorus ferrugineus (Olivier). The presence of the RPW provides an opportunity to establish robust models and detection and control techniques.

As part of a research program, we assessed various techniques for controlling the red palm weevil, such as pheromone traps, traditional traps, chemical treatment, eco-friendly organic treatment, and electronic devices. Our study's results indicated that both chemical and organic treatments significantly decreased the RPW population in the treated plots. Notably, the organic treatment proved to be more effective, diminishing the RPW population by about 70%. The electronic device used spectral analysis of audio recordings to extract spectrum features, which were attributed to specific descriptors or a "fingerprint" of RPW activity in the trunk of palm trees. The device's ability to detect RPW was demonstrated. It effectively decreased the number of RPW appearances on trees in the high-activity zone by providing an electrostatic protective barrier.

Furthermore, our study highlights the potential of emerging technologies such as drones, remote sensing, artificial intelligence, and the Internet of Things for effective pest management and water efficiency in date palm plantations in the future.

Introduction

The date palm (Phoenix dactylifera L.) holds a unique position in the Arabian Peninsula, not only as the oldest fruit tree but also as a cornerstone of agri-food systems. Its cultivation is deeply intertwined with the local cultural heritage and social and economic life. However, this ancient practice is facing mounting challenges: water scarcity, soil and water salinity, low soil fertility, and the threat of pests and diseases. As climate change continues to unfold, these challenges, particularly those posed by pests, are expected to escalate. The date palm, a native and widely accessible tree, is a testament to nature's resilience. It has weathered the test of time, standing tall as a symbol of the Middle East and North Africa (MENA) region's cultural heritage. This region, responsible for about 90% of the world's date production, has relied on the date palm for more than 5,000 years (Rahman *et al*., 2022). Particularly in the oases of the Middle East, the date palm has demonstrated its ability to withstand harsh weather conditions and adapt to various stressors such as droughts, floods, extreme heat, poor soil quality, salinity, and pests. With its deep-rooted history, the date palm has significantly affected the economy, society, and environment. In the United Arab Emirates, the earliest evidence of date palm seed usage dates back to 5290-4940 Cal B.C. and 4810-4540 Cal B.C. on Dalma Island in Abu Dhabi. Technological advances and government support for farmers have led to a remarkable increase in the number of date palm trees in the UAE. The actual date tree population in the UAE is about 40 million, with 8.5 million in the Al Ain Region alone (Al-Muaini *et al*., 2019; UAEU, 2022). In 2015, the United Nations Food and Agriculture Organization

One of the longest-running research programs on date palm in the region (since 2001)

(FAO) recognized the Al Ain and Liwa oases as globally important agricultural heritage systems for dates because of their significance as repositories of genetic resources, biodiversity, and cultural heritage (Gulf News, 2015).

The FAO reports that date palm production spans a global area of more than 1.09 million hectares, with a yearly production exceeding 8.5 million tons. Approximately 5,000 date palm varieties are found worldwide, with 55.8% of global production concentrated in Asia and 43.4% in Africa. The Arab region accounts for more than 77% of date production, with approximately 160 million palm trees and about 6.6 million tons produced annually. The United Arab Emirates is among the top ten date palm-producing countries, having produced 323,478 metric tons in 2019.

The value of date palms as a cash crop is undeniable, but their growth is seriously threatened by the red palm weevil (RPW) Rhynchophorus ferrugineus (Olivier). Even a low pest population can lead to RPW infestation, and a mere 1% infestation rate is enough to trigger control measures (Manee *et al*., 2023). This underlines the pressing need for effective pest management strategies to safeguard date palm cultivation. The RPW, originally from Southeast Asia, has become one of the most invasive palm pests worldwide. Its spread has been particularly devastating in the Arabian Gulf and the Mediterranean basin countries. RPW established a presence more than 30 years ago in the Near East, specifically on the date palm, and has since significantly expanded its geographical range (FAO, 2020). Several studies have identified the factors that have facilitated the wide-ranging distribution of the RPW in this region: favorable environmental conditions for it in the Gulf region, its continuous life cycle, its highly efficient flying ability, as well as its ability to use date palm trees as a host throughout the year. All life stages of the RPW, from egg to adult, occur within the infested trees, resulting in rapid multiplication. It is worth noting that the RPW population is predominantly female, following the pattern of most pests.

The NENA region is a significant contributor to the global date production. However, the region has been facing a severe challenge in recent years in the form of the RPW, which has adversely affected the livelihoods of nearly 50 million farmers in the area. The Mediterranean countries have been particularly affected, with millions of dollars'

Ajwa date palm at ICBA research station, 2023, Dubai, UAE.

worth of date palms being lost annually because of the RPW. The RPW is a pest that poses a significant threat. According to the FAO, the situation is quite alarming in many countries, such as Egypt, where RPW was found on 94% of date palm farms in 2022. The country has been investing USD 5.7 million annually in ongoing RPW treatment programs to address this problem. However, despite these efforts, the loss of date palms and associated foregone revenue is up to USD 213 million annually. In Saudi Arabia, the RPW has made its presence felt, infesting 53% of date palm farms in 2022. This has necessitated an annual investment of USD 34.4 million in ongoing RPW treatment programs. The economic toll is staggering, with the loss of date palms and associated foregone revenue reaching USD 401 million annually. These numbers underscore the severe economic impact of the RPW pest on the date palm industry in the NENA region, thus demanding immediate attention and action to prevent further damage. According to Elsabea *et al*. (2009), the estimated losses due to 1% to 5% infestation of palms range from USD 5.18 to 25.92 million. Moreover, indirect losses would increase this amount significantly. However, curative treatment of palms in the early stage of the attack resulted in savings estimated to range from USD 20.73 to 103.66 million. The RPW alone is responsible for destroying Euro 480 million worth of date palms yearly in the Mediterranean countries and it affects nearly 50 million farmers worldwide. Managing the date palm is critical for agroecosystems' sustainability, as continual adjustments in their structure and management strategies are necessary to enhance production in harsh environments. Effective pest control is particularly important in date palm production, given that the FAO reported a 30% decline in global production in 2013 due to diseases and pests.

The Gulf Cooperation Council (GCC) region, where date palm trees are the primary fruit trees, is facing a devastating impact caused by the rapid spread of the red palm weevil. To combat this problem, innovative solutions are required. Early detection is crucial for effectively controlling RPW; however, no effective devices or technologies are currently available for field application. As a result, the detection of weevils primarily depends on the experience of skilled personnel, making the process time-consuming, expensive, and inefficient. The successful implementation of the proposed approach is contingent

Khnizi date palm at ICBA research station, 2023, Dubai, UAE.

upon understanding the RPW life cycle as well as the manifestation of palm trees' response to it. Timely, precise, reliable, and cost-effective data and information are required to optimize customary agricultural practices such as irrigation, fertilization, pollination, and harvesting related to date palm cultivation. In addition, accurate data and information are critical to safeguard plantations against mass infestations, such as the RPW. Data-driven agriculture is becoming increasingly important for various agricultural applications. It is worth noting that it is not a luxury or an expensive solution, as various data sources can be provided by open-source and government agencies.

The International Center for Biosaline Agriculture (ICBA) boasts a palm plantation that showcases the 18 most common varieties of palm trees in the UAE and GCC region. This 23-year-old plantation is a unique study area that allows for the comparison of various varieties of date palms under salinity stress (Al-Dakheel *et al*., 2022; Hammami *et al*., 2024). The plantation spans nearly 3 hectares, making it an ideal experimental site for having a comprehensive collection of datasets to test and develop new innovative approaches toward early and better detection, as well as control and eradication of the RPW. The rich dataset and various tools and technologies employed at the plantation enable researchers to understand the date palm's behavior and its linkage to its bio-physiological status and various biotic and abiotic stresses. It is crucial to note that, although the RPW has been detected at the ICBA palm plantation, this discovery provides an opportunity to establish robust models and detection and control techniques.

Pest and disease management

Red palm weevil

Red palm weevil Rhynchophorus ferrugineus (Olivier), a reddish-brown beetle of the Curculionid family (Coleoptera: ***Curculionidae***), is a global threat to palm trees. It measures 2.5-4.0 cm in length and uses its long snout to lay eggs in the crevices of the palm tree. The hatched larvae tunnel into the tree's tissues, leaving behind galleries filled with frass, a mixture of feces and wood particles, as a characteristic indicator of infestation.

Red palm weevil larvae can cause severe and irreparable damage to palm trees, leading to death. The damage can result from losing the apical bud or from the onset of fungal disease. To safeguard palm tree populations, it is crucial to take proactive measures to

Jabri date palm at ICBA research station, 2023, Dubai, UAE.

identify and control red palm weevil infestations. Various chemical, biological, and cultural control techniques are employed to manage the infestation. The key to success lies in early detection and swift control measures, empowering farmers to prevent the spread of infestation and minimize the damage caused by the pest.

Several preventive measures are recommended to effectively manage and contain the spread of RPW. First, regularly cleaning and pruning palm trees is important, as this can help identify and remove any infested areas before they spread. Second, infected trees and waste must be properly disposed of in a timely manner to prevent further contamination. In addition, it is advised to apply tar to wounds after pruning to prevent egg-laying.

Furthermore, it is important to obtain new seedlings from uninfected farms and exercise caution when conducting agricultural operations, particularly with regard to irrigation and fertilization. Properly conducting these activities can help prevent the spread of RPW and keep palm trees healthy. Adhering to these guidelines can help limit the spread of RPW and maintain the health of your palm trees.

Materials and methods

Experimental design and treatments

In 2001, a long-term experiment began at ICBA's research station located at 25o13'N and 55o17'E to investigate the growth and development of different local and imported date palm varieties. The experiment involved 18 date palm genotypes, with ten from the UAE, seven from Saudi Arabia, and one from Iraq. The trees were subjected to four different treatments that varied in the salinity of the irrigation water: 0.4, 5, 10, and 15 dS.m-1. The trees were planted in 2001 and arranged systematically in rows, with each salinity level containing trees spaced 8 by 8 meters apart. A 20-meter gap was left between each group of five plants.

Recently, the RPW was detected at the ICBA palm plantation, providing an opportunity to study the effectiveness of different control techniques for this pest. From 2019 to 2022, three treatments were tested for the control of RPW, which covered all infestation levels, categorized as low, medium, and high, since the field was naturally infested with the pest. RPW Treatment 1 used the PalmGuard electronic device to control the pest in selected trees, while the remaining part used a control for the experiment (Figure 1). RPW Treatment 2 involved injecting chemical treatment, while RPW Treatment 3 involved injecting organic treatment. Each treatment also included using pheromone traps to monitor the number of RPW in each treatment (Figure 1).

The treatments used in this study are as follows:

Treatment 1: used an electronic device called PalmGuard provided by PalmaLife LLC to monitor pests in selected trees while the remaining part of the experiment had control trees. The electronic device is a solar-powered monitoring device for palm trees that is supposed to be able to detect pests such as the red palm weevil. It has two highly sensitive microphones that perform acoustic diagnostics to highlight the sound signals for the RPW. The device creates an electrostatic barrier to repel insects with varying electric field strengths chosen based on insect sensitivity. The electrostatic screen is a grid of conductors that repels insects. The high-voltage converter doesn't pose any danger to people or animals. The devices were placed in the upper part of the palm tree trunk. The dynamics of RPW appearance and the general state of the palm trees were monitored at the trees with the device installed, before and after activation of the protection function, and at the control trees (“no-device palms”) within each zone. The observations were carried out through visual inspection, constant video recording, and audio recording within each zone.

The electronic device for RPW control installed in the field.

The application of the chemical treatment injection by a company’s technical team.

The application of the chemical treatment injection by the ICBA team.

Treatment 2: on the other hand, was based on a tree microinjection chemical, which was provided and applied by a well-known supplying company. The active ingredient in use was emamectin benzoate, with a concentration of 4.5% or 9.5% TMI optimized formulation. The application was through tree microinjection, with four injection points per tree. The application used Aretor 4.5% (48 mL per tree) and Aretor 9.5% (21 mL per tree), with a pre-harvest interval of 90 days. A single application is required per year.

Treatment 3: involved injecting organic treatments using cassava-based bioformulations offered by the Central Tuber Crops Research Institute (ICAR).

The electronic device for RPW control installed in the field.

The application of the chemical treatment injection by a company's technical team.

The application of the chemical treatment injection by the ICBA team.

Preliminary study:

In order to prepare for a trial, we conducted an experiment to determine the most appropriate traps for the purpose at hand. After careful evaluation, we chose a specific dry trap that proved highly effective in trapping RPW without necessitating frequent servicing. This trap comes with two options for trapping RPW and RPW pheromone: the "attract-and-kill" method and the dry trap, which relies on electromagnetic diffusion of semiochemical signals. RPW pheromone traps are better suited for the UAE environment than traditional food-baited bucket traps that require regular refilling with food bait and water. This is particularly relevant for the UAE, where high temperatures result in high evaporation rates. These findings align with the information outlined in J.R. Faleiro's recommendation reported on the management practices for the red palm weevil (FAO, 2020).

Further Studies at the ICBA research station

The following techniques have been tested in addition to the initial trials for controlling red palm weevil RPW:

1. Implementation of modified RPW pheromone traps and remote sensing technology to detect and manage RPW infestations in date palm plantations at an early stage.
2. Evaluation of TrapGIS, an AgrIOT module, to streamline RPW trap management and enhance the efficiency and cost-effectiveness of integrated pest management (IPM) programs.
3. Deployment of drones integrated with AI and IoT for early detection, control, and supervision of RPW infestations in date palm plantations.

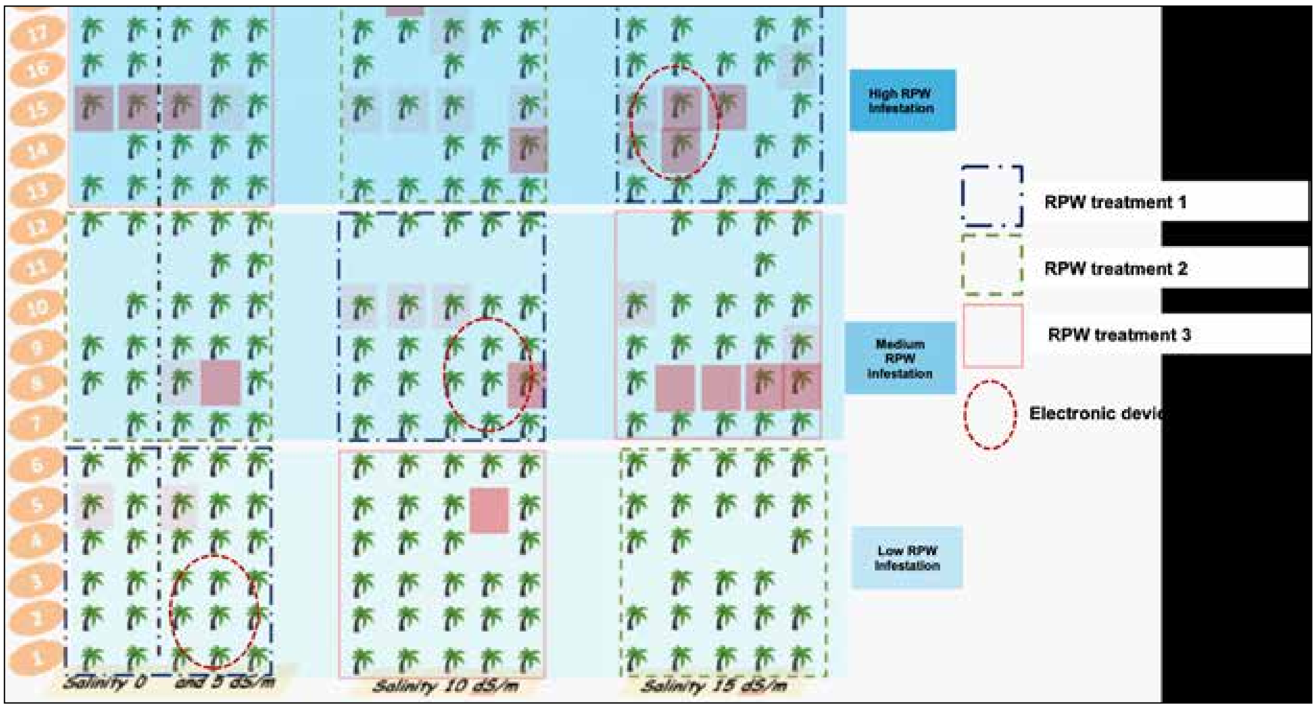

Figure 1: The experimental layout for the RPW trial in three field zones and the RPW infestation pattern in a date palm experiment at ICBA. Dark pink denotes a confirmed attack of RPW and light pink denotes an initial infestation/probably infested plant

4. Incorporation of drone-based data collection into a GIS-based AI analysis platform for continuous monitoring of date palm plantations.

5. Utilization of multispectral drone imagery and Object-Based Image Analysis (OBIA) for comprehensive analysis of date palms and vegetation indices to facilitate qualitative assessment.

Statistical analysis

We analyzed the data collected at the experimental site using R software version 4.0.5 for statistical analysis and graph creation. We conducted an ANOVA test to measure the impact of the treatments on the RPW population. We also used Duncan's multiple range test to determine the significance of various applied chemical and organic treatments relative to the control on RPW. The probability level used for the calculations was set at $P \leq 0.05$. In addition, we analyzed the data collected from the electronic device using the Mann-Whitney test. Finally, we created some of the graphical representations of the results using Microsoft Excel 2007.

Results

1. The effectiveness of chemical and organic treatments

Red palm weevil is a major pest that causes extensive damage to date palm trees. Several techniques have been evaluated as a part of the date palm research program to control its infestation. These techniques involve tree microinjection with chemical and organic treatments and the use of pheromone traps to monitor the number of RPW in each treatment.

The results of our study, which tested and compared the effectiveness of chemical and organic treatments on untreated trees, showed that both treatments effectively controlled RPW infestation. This was especially true when used under an integrated approach involving field cleaning and the best farming practices. RPW exists throughout the year. The RPW population displayed a general pattern of two yearly peaks, one in March-April-May and the second in November (Figure 2). These findings confirmed the possibility of RPW management, which can be implemented in an effective pest control strategy.

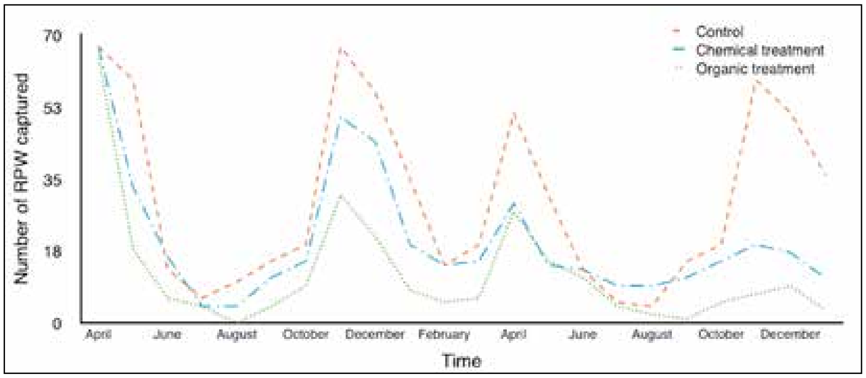

Figure 2: Number of RPW captured using RPW pheromone traps with the chemical and organic treatments relative to the control.

Although the untreated trees showed no decline in RPW infestation, both chemical and organic treatments significantly decreased the RPW population in the treated plots. Notably, the organic treatment emerged as the most effective option in diminishing the RPW population by about 70% (Figure 2).

These findings hold promise for the development of robust strategies to combat RPW infestation in date palm trees.

Figure 3 summarizes the number of weevils caught and their distribution, including the outliers. Both treatments had a significant impact on controlling RPW infestation. However, the results also revealed a slight increase in the RPW population during peak RPW activity, even with intervention (Figure 3). It is important to note that the RPW exists year-round, making single RPW control practices based solely on insecticides (organic or inorganic) limited because of the feeding habits of the RWP. In addition, the RPW population is primarily female, leading to rapid multiplication.

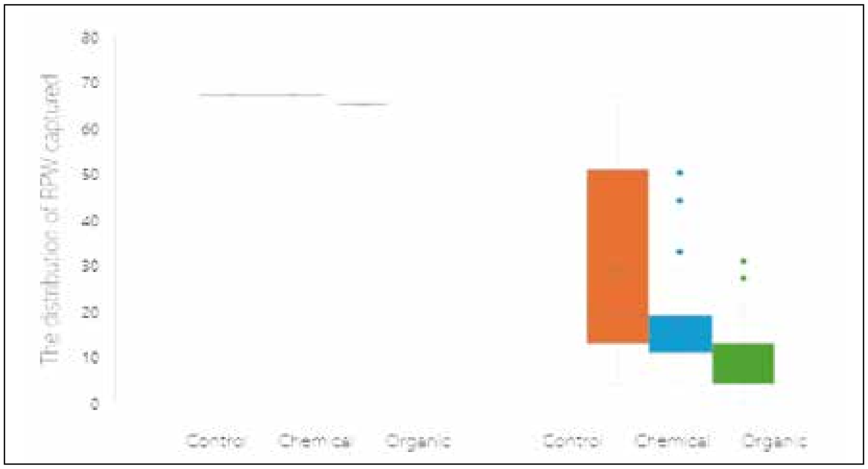

Figure 3: Boxplot presentation of RPW distribution before (during April) and after the intervention (for 21 months). Different letters in the same intervention time indicate significant differences at $P < 0.01$ by Duncan's LSD test.

The life cycle of RPW is continuous, and it is not a periodic pest. RPWs are also strong flyers, making them highly mobile and capable of moving easily from infested to untreated field areas, even after interventions have been made to control their population.

Several studies have confirmed the effectiveness of using cassava-based formulations in controlling the banana stem weevil. Kannan *et al.* (2021) conducted a study to evaluate the effectiveness of biopesticides against the banana stem weevil Odoiporus longicollis (Olivier). They found that Avaya and chlorpyrifos had 100% mortality rates, while CTCRI-Nanma and Nimbecidine had 91.66% mortality rates. Field observations indicated that Nimbecidine and cassava-based Nanma significantly decreased infestation. Moreover, Pushparaj and Subramannian (2022) conducted an on-farm assessment of the impact of cassava leaf extract biopesticide on controlling banana pseudostem weevil and popularization of the technology. They confirmed that the biopesticide had better results on the plants than those treated with chlorpyrifos.

Numerous studies have been conducted to test the effectiveness of chemical treatment for controlling apical infestation. According to El-Shafie *et al.* (2024), Aretor 9.7, which contains emamectin benzoate, was found to be more effective than imidacloprid. It is recommended to wait for at least three months before harvesting cultivars Barhee and Sukari. However, the results of this study should not be extrapolated to other cultivars.

2. Results of testing an electronic device as a technique for red palm weevil control

- **Monitoring function**

We made audio recordings using PalmGuard devices to study their monitoring function. We analyzed the characteristic sounds produced by red palm weevils in tree trunks, and we used specific descriptors to predict RPW appearance (as shown in Figures 4-5). We used the spectral analysis of audio recordings by PalmGuard to effectively extract spectrum features that can be attributed to specific descriptors (a fingerprint) of RPW activity in the trunk of palm trees.

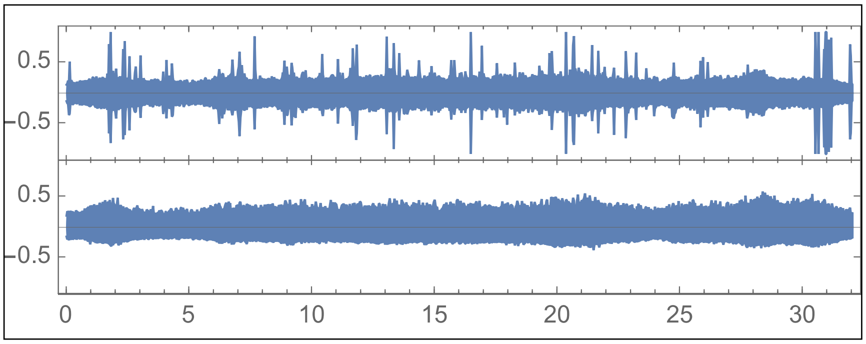

Figure 4: Waveform of the 32-second stereo (two-channel) audio recording from the conductive channel of audio file 1. For each channel in the figure, the audio signal is visually represented as a sequence of real values ranging from -1 to 1. A typical recording contains a mixture of environmental noise and an informative signal from the pests.

- **Protection function**

During the trial period, we carried out monitoring and visual inspection, and detected no pest in the zone with low natural infestation. However, in the zones with medium and high natural infestation, we detected RPW activity on three trees, which prompted the installation of protection devices on all of them. After two months of monitoring RPW activity on both the trees with the protection devices and the control trees without them, we observed that RPW activity on the trees with the devices installed was eliminated compared to the control trees. This is depicted in Figure 6, where the green line represents the trees with the devices and the blue line represents the control trees.

The device's protection function significantly decreased the number of RPW appearances on the trees in the zone of moderate activity and in the high-activity zone. This decrease occurred in the first month of the protection function work and persisted after that, even during the months of peak activity. We observed that one tree with the device began the restoration process without using insecticides after the infestation stopped.

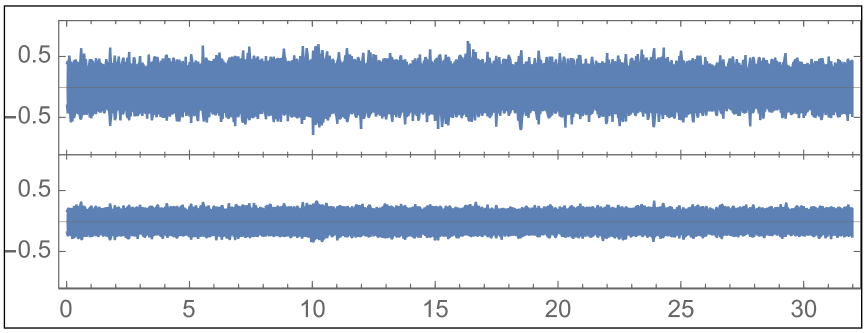

Figure 5: Scaled waveform of the 32-second stereo (two-channel) audio recording from the air channel of audio file 1. For each channel in the figure, the audio signal is visually represented as a sequence of real values ranging from -1 to 1, followed by scaling by a factor of 8 for better visibility. A typical recording contains a mixture of environmental noise and an informative signal from the pests.

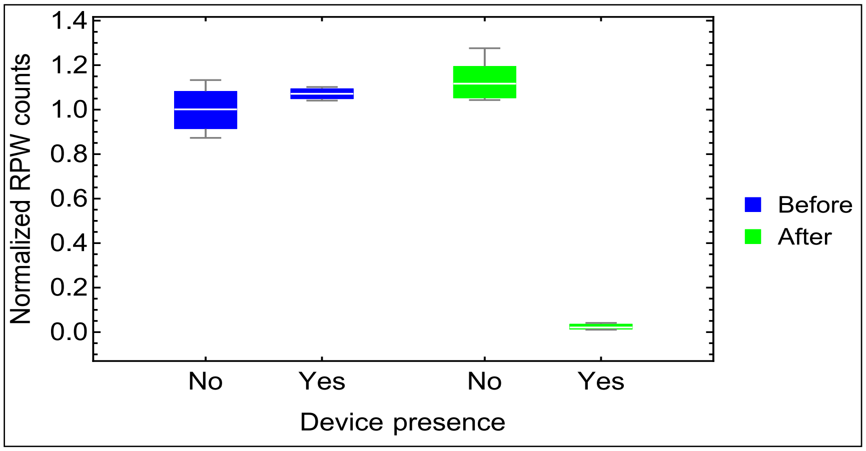

Figure 6: Normalized numbers of RPW appearances on three trees with the PalmGuard device installed and on ten control palm trees in zone 2 were collected before the PalmGuard protection function initiation (blue) and two months after (green). The RPW counts were normalized to the mean value of the leftmost distribution in the figure. Mean RPW counts for the yes/after conditions are significantly smaller than for the no/after conditions (Mann–Whitney test: statistical value = 30, P value = 0.01), and this does not vary significantly between the no/before and yes/before conditions (Mann–Whitney test: statistical value = 7, P value = 0.15).

Electronic devices can effectively monitor and protect against red palm weevil activity. By conducting a spectral analysis of audio recordings, RPW activity features can be extracted. The protection functions of these devices have been found to decrease RPW appearances in moderate- and high-activity zones markedly.

The tested electronic devices can detect the sound made by adult RPW. Bioacoustic detection techniques are commonly used to identify infestations in coconut and date palm trees caused by RPW larvae. These techniques can detect the sound produced by feeding larvae, but a trained ear is required to distinguish it from other sounds (Soroker *et al*., 2004). However, this technique has some limitations. In the early stages of infestation, the sound is too low to distinguish it from background noise. Detection must be performed on each tree individually, and larvae produce sounds that can be confused with sounds produced by other insects, small animals, or wind-induced tapping noises. Although the technique has the potential to enable early detection, it has some flaws. One of the major flaws is ambient interference with low energy emitted by younger larvae (Soroker *et al*., 2013).

It is recommended that the next generation of the tested device include an automatic RPW counting function. Based on the results of our study, it is also appropriate to conduct a test on a larger sample of palm trees (more than 50). In addition, it is recommended that the possibility of decreasing the cost of the device and increasing the number of protected palms from one device be considered.

To make the device more effective, a GPS function to locate it when working on large plantations is suggested.

3. Other examples of RPW control techniques: modified RPW pheromone traps

The red palm weevil has been a consistent threat to date palm plantations, necessitating the development of early detection systems that have undergone testing and validation. Remote-sensing technology has also been employed to identify palms and detect early RPW infestations. To achieve this, the available RPW traps were modified to include an automatic RPW counting function for data collection. The collected data are then integrated into a GIS-based AI analysis platform to monitor date palm plantations effectively. The system is designed to manage, map, register, and monitor these plantations. This technology has shown promising results in the early detection and control of RPW infestations by enabling early detection and intervention in real time, optimizing the use of resources and decreasing

Figure 7: Example of the system tested with AgrIOT traps for RPW control and the geospatial agricultural and real-time data management platform, AgrIOT. On the left, the pheromone trap shown in the blue oval is a pheromone trap amended by the RPW counting scanner connected to a mobile app.

excess or unnecessary pesticide use. However, the effectiveness of these tools still requires careful attention to ensure their efficiency while identifying technical solutions to make them more cost-effective and affordable.

For example, we tested TrapGIS. TrapGIS is an AgrIOT module designed to manage, map, register, and monitor red palm weevil traps (Figure 7). This module comes with mobile applications that can be used for collecting data in the field and a web portal for pest management. Using this module will make an IPM program more efficient and effective while decreasing costs. The AgrIOT platform is protocol-independent, but it is recommended that LoRaWAN be used for wireless Internet of Things (IoT) sensor networks. With a single AgrIOT base station, it is possible to collect data from more than 1,000 low-power sensors within a range of at least 1.5 km, making this a cost-effective solution. Registered users can access the data through AgrIOT mobile apps and the web portal.

4. Drone- and AI-enabled solutions

To counteract the devastating effect coupled with the rapid spread of red palm weevil in the GCC region, where date palm trees are the main fruit trees, innovative solutions are needed. Unmanned aerial vehicles (UAVs) such as drones have emerged as a breakthrough technology, allowing disruptive solutions to complex problems in recent years. Drones can be coupled with new technologies such as AI and IoT in order to achieve early detection, control, and management of RPW within the perspective of an area-wide integrated pest management approach (Jintasuttisak *et al*., 2022). In fact, a robotic and computer science approach can rely on the double ability of drones to collect data (e.g., remote-sensing plantation imagery) (Figure 8) and conduct precise field operations (e.g., spraying pesticide on a specific tree). Understanding the RPW life cycle and the manifestation of palm trees' response to it is crucial for the proposed approach's success.

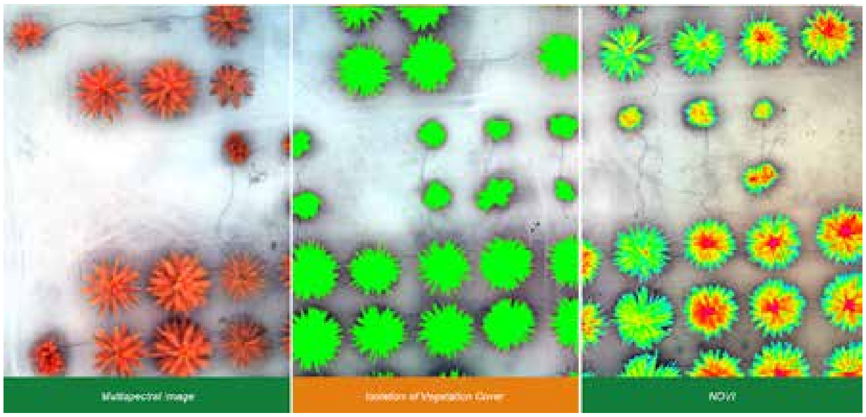

Figure 8: Example of multispectral drone imagery – ground sampling distance = 8 cm, prepared by Dr. Elbattay and partners.

This research also involves testing and implementing a system of the Internet of Things and drone-based data collection integrated into a GIS-based AI analysis platform for monitoring date palm plantations (Palm Smart Management Solution). Since 2019, ICBA has been using a wide range of drones and remote-sensing sensors for better data integration and standardization (Figure 9). ICBA also conducted a joint experiment with Zayed University in 2019 to study the use of drones for date palm pollination. This experiment involved students who received an international award during the 2019 International Student Conference on Environment and Sustainability (ISCES 2019). Figure 8 shows multispectral drone imagery, with a ground sampling distance (GSD) of 8 cm, is highly effective for date palm monitoring. This technology provides in-depth, high spatial resolution images and allows for adaptive acquisition according to the crucial stages of the tree development cycle. The precision and adaptability of multispectral remote sensing make it an invaluable tool in the agricultural management and health assessment of date palms.

The figure 9 illustrates the segmentation of multispectral images using Object-Based Image Analysis (OBIA). This technique shifts the focus from pixel-based to object-based analysis, enabling the identification of each date palm as a distinct object. Various parameters related to the canopy's size, shape, and symmetry can be utilized for more detailed date palm analysis.

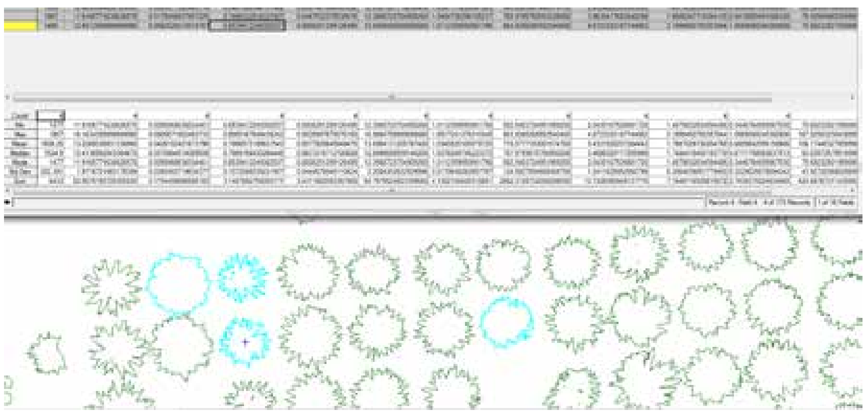

Figure 9: Example of Date Palm Object Based Image Analysis from drone imagery – ground sampling distance (GSD) = 8 cm, prepared by Dr. Elbattay Ali, and partners.

The figure 10 demonstrates how combining remote sensing vegetation indices (e.g., NDVI or red edge VI) with Object-Based Image Analysis (OBIA) enables qualitative identification of date palm health. This method allows the development of ML approaches relying on the capability of comparison with peer trees in the same plantation and with the historical remote sensing data of the same tree, facilitating the detection of abnormalities.

Figure 11 shows how thermal imagery captured during extreme summer heat reveals stressed trees with abnormal evapotranspiration patterns compared to healthy ones. The flexibility of drones allows for precise acquisition timing, synchronizing with peak heat stress. This facilitates the identification of RPW-infested trees, which struggle to transport water from roots to canopy due to trunk infestation.

The series of figures 7-10 highlights the transformative potential of drones in palm smart management solutions. Multispectral and thermal drone imagery, coupled with Object-Based Image Analysis (OBIA) and machine learning, enable detailed monitoring and early detection of issues like RPW infestation. These advancements showcase the pioneering role of the center in exploring and implementing cutting-edge remote sensing technologies for enhanced date palm management.

5. Red palm weevil management via integrated pest management strategy

The management of RPW infestations is best achieved through an integrated pest management (IPM) strategy encompassing several measures. Among these measures is a regular inspection of palms to detect infestations, using pheromone traps to capture adult weevils, and applying preventive and curative chemical treatments. Severely infested palms should be removed or eradicated. Adherence to good agronomic practices that limit RPW attack and the adoption of both visual observation and pheromone traps are also recommended (Alotaibi *et al*., 2022). Quarantine measures could also be employed to regulate the movement of planting materials. It is imperative to implement good agronomic practices such as field sanitation, control of palm density, irrigation, and the removal of fronds and offshoots. It is important to maintain date palm trees by properly pruning and cutting the rachis base. This practice helps promote healthy growth, control the RPW, and maintain overall plant health. Effective biological control agents such as fungi and nematodes should also be deployed to combat the pest. These agents can reach the pest and establish themselves in the field, thus contributing to the long-term management of red palm weevil infestations. RPW monitoring and early warning systems that use geographic information systems (GIS) can be useful in identifying where best to deploy resources. This approach effectively directs resources to the areas most needing attention, resulting in better outcomes.

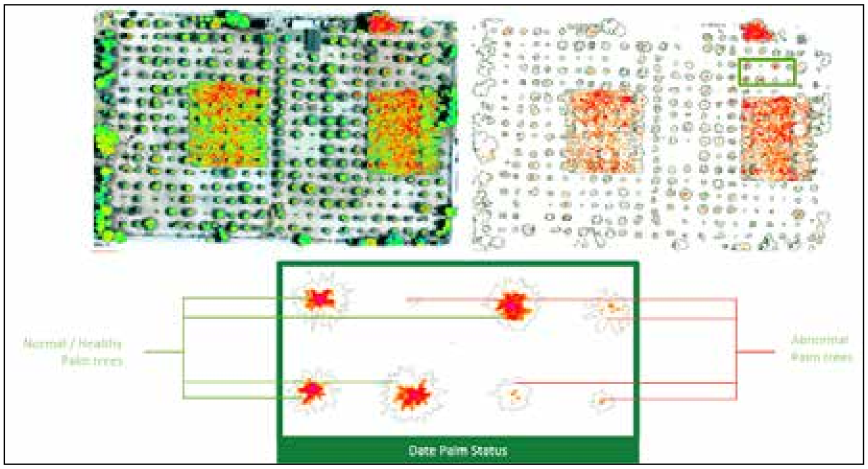

Figure 10: Example of a machine learning approach to detect abnormal date palms, prepared by Dr. Elbattay Ali and partners.

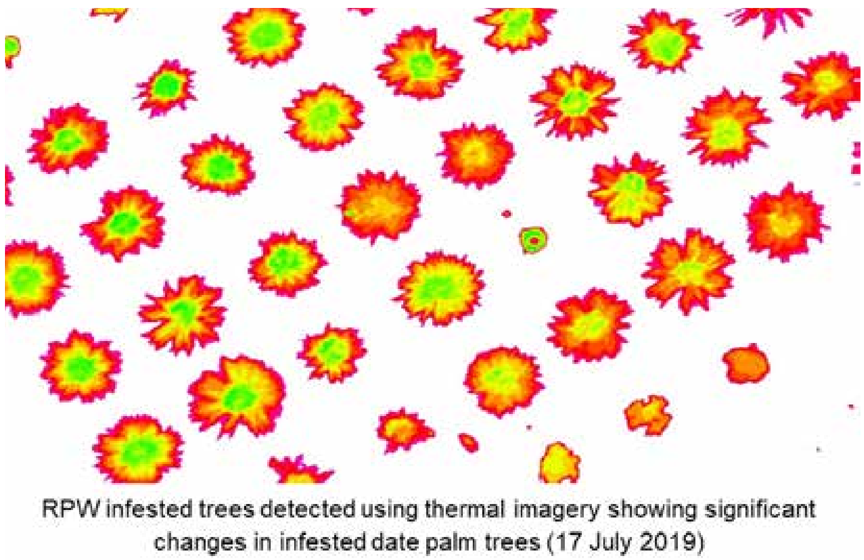

Figure 11: Example of Thermal drone imagery for Early Detection of RPW– ground sampling distance (GSD) = 12.5 cm, prepared by Dr. Elbattay Ali, and partners.

Conclusions

The International Center for Biosaline Agriculture has established a research program to improve date palm cultivation. This program covers several areas of study, including irrigation, water conservation, fertilization management, pest control, and fruit quality. ICBA collaborates with national and international partners to collect and analyze data on irrigation practices and farming techniques. ICBA is currently evaluating pest control technologies, developing innovative methods to overcome challenges posed by the red palm weevil, and working on improving the quality of date palm fruit in saline environments. In this regard, ICBA is exploring the use of UAVs and other advanced technologies to detect, control, and manage RPW infestations quickly. In 2001, ICBA created a date palm plantation, which covers almost 3 hectares, at its experimental station in the UAE. The plantation's primary objective is to guarantee the long-term sustainability of this significant crop by developing sustainable management strategies. These strategies aim to mitigate the impact of pests, diseases, and other stressors. The plantation enables ICBA to collect a comprehensive dataset, test innovative approaches, and assess the various characteristics of 18 date palm varieties over an extended period. This study area provides an ideal platform for developing strategies that will ensure the effective management of date palm plantations, thereby securing the long-term sustainability of this crucial crop.

ICBA date palm research also aims to implement an integrated approach that combines the use of genomic tools to understand the molecular basis of RPW resistance in date palm varieties and the use of UAVs and drones to enable early detection of infestation, which together can significantly change the pest and disease complexity in date palm. This research work also involves testing and implementing a system of the IoT and drone-based data collection integrated into a GIS-based AI analysis platform for monitoring date palm plantations (Palm Smart Management Solution). As date palm production in the region faces a host of challenges, it is important to develop integrated date palm management solutions. Therefore, ICBA's research program on date palm aims to meet the need for such solutions and support efforts by other organizations to improve the livelihoods of date palm producers in the region and beyond.

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